New Developments and Capabilities at the Coupled Cyclotron Facility at Michigan State University

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• National user facility for rare isotope research and education in nuclear science, astro-nuclear physics, accelerator physics, and societal applications

• One of the three nuclear-science flagship facilities in the US: RHIC at BNL, CEBAF at JLAB, NSCL at MSU [2007 NSAC Long Range Plan]

• Largest university-based nuclear physics laboratory in the United States: 10% of U.S. nuclear science Ph.D.s

• Over 500 employees (NSCL+FRIB), incl. 45 graduate students, and 43 faculty – over 700 users

• Graduate program in nuclear physics ranked 1st [U.S. News and World Report]

• NSCL provides accelerated beams of heavy ions from oxygen to uranium, including rare isotope beams

• Michigan State University has been selected to establish FRIB, the Facility for Rare Isotope Beams
Coupled Cyclotron Facility at NSCL

2 ECR ion sources
2 coupled cyclotrons: K500 + K1200
primary beams: oxygen to uranium
K500: 8 - 14 MeV/u, 2-8 eμA
K1200: 100 - 170 MeV/u, up to 2 kW

A1900 fragment separator
to produce rare isotope beams
by projectile fragmentation
Beam list intensities are typical intensities for experiment planning purposes and are maintainable for extended time periods.
Coupled Cyclotron Facility (CCF) delivers a different primary beam every 5 to 7 days, typically 30 beam changes per year.

The development of new primary beams (isotope and energy) is driven by user demand.
Rare Isotope Beams produced at NSCL

more than 1000 RIBs have been produced (2001-2013)
more than 870 have been used in experiments

Neutron Number

Proton Number

Observed isotopes
Experiments at NSCL
Produced at NSCL
Primary Beams
Overview of the Fragment Separation Technique

Example: $^{86}\text{Kr} \rightarrow ^{78}\text{Ni}$

- **$^{86}\text{Kr}^{14+}$**, 140 MeV/u
- **$^{86}\text{Kr}^{34+}$**, 12 MeV/u

- Transmission of 65% of the produced $^{78}\text{Ni}$
- $\Delta p/p = 5\%$

- Fragment yield after target
- Fragment yield after wedge
- Fragment yield at focal plane
A1900 Diagnostics Setup and Particle Identification

K1200

10 m

stripping foil

production target

image-1

image-2

wedge

image-3

focal plane

Detector Setup in Focal Plane Box

2 PPACs

variable slits

timing viewer

scintillator

Ge detector

PIN stack

scintillator

position x, y, x', y'

ΔE, Etotal

ΔE, Etotal, TOF

alternative

Sn

N=Z+3

124Xe (140 MeV/u) + 9Be (390 mg/cm²)

Camera/viewer

time of flight [a.u.]

energy loss [a.u.]
The Reacceleration Concept

ReA post-accelerator

Highly charged ion beam

Magnetic sector

Room-temperature RFQ

RB

Superconducting RF linac

0.3 - 3 MeV/u

Electrostatic sector

Achromatic Q/A separator

Production & In-flight separation

stable heavy ion beam

Thin foil target

>100 MeV/u

<1 eV

60 keV

600 keV/u

12 keV/u

MHB

EBIT charge breeder

1+ → Q+

Thermalization

Trapped ions < 200 eV

>80 MeV/u

He gas-cell

>100 MeV/u
Rare isotope beams from A1900 fragment separator go through a momentum compression stage based on magnetic elements and variable and wedge-shaped solid degraders before injection into gas cell.

**Rotable Degraders:**
aluminum, thickness ~0.2 - 1.5 mm, angle 0-45 deg

**Wedge Degrader:**
fused silicon, thickness ~1mm, angle 5 mrad

Particle ID with silicon PIN (dE vs. TOF)

76Ga 76Zn
Gas Thermalization – Gas Catcher

120 cm gas catcher from Argonne National Lab operates with helium at ~100 mbar and -5°C

gas catcher mounted on high-voltage platform with variable potential up to 60 kV

total extraction efficiency: ~10%
Gas Thermalization – Extraction

• ions are extracted in 1+ and 2+ charge states
• mass analyzer allows to select single mass
• activity can be detected with beta-decay counter
• extraction efficiency into single mass depends on chemistry with impurities

![Diagram showing gas catcher, extraction RFQ, FC/β, MCP, and beam to low-energy experimental area (LEBIT, BECOLA) or to reaccelerator (charge breeder).]

Fraction of $^{37}\text{K}^+$ ~ 94%
EBIT charge breeder
Q/A mass separator
multi harmonic buncher (MHB)
room-temperature RFQ
2 beta=0.041 cryomodules with 2 + 6 QWR
1 beta=0.085 cryomodule (to be installed in 2014)
EBIT Charge Breeding Principle

- Singly charged ions quasi-continuously injected in the high-current density electron beam
- Ions trapped by trap electrodes & the e-beam space-charge potential
- Highly charged produced by electron-impact ionization (i.e., charge breeding)
- Pulsed extraction of highly charged ions
The ReA EBIT Charge Breeder

Requirements for ReA charge breeder:
- Breeding time < 50 ms (for short-lived isotopes)
- Efficiency: 20% - 50% (inject.-breeding-extract.)
- Charge capacity: up to $10^{10}$ positive charges
- Low contamination level...

Key design parameters:
- High electron current: up to 2.4 A (large cathode)
- E-beam energy <30 keV (e.g. Ne-like U$^{82+}$)
- Current density (6 T): $\sim 10^4$ A/cm$^2$
- Reduced contamination: 4-K trap structure
ReA EBIT Charge Breeder
Q/A Mass Separator

Design parameters:
- Resolving power ~100 at 120 $\pi$ mm mrad
- Achromatic within $\Delta E/E \sim 3\%$
- Accept EBIT beams of large energy spread

Double-focusing spectrometer

EBIT charge breeder
superconducting magnet (6 T)

test beam ion source

45° electrostatic bends

90° dipole magnet

N+ beam to reaccelerator

1+ rare isotope beam

electron collector

electron gun (<5A)
EBIT Commissioning Results

Residual Gas - no EBIT injection

Charge-bred $^{85}$Rb from ion source
Total capture efficiency is in good agreement with expected capture efficiency (~30%) for an electron beam current density of ~350 A/cm²
Multiharmonic Buncher and RFQ

**Multiharmonic Buncher (MHB)**

Used to achieve beam properties required for nuclear physics experiments:

- energy spread: < 1keV/u
- bunch length: ~ 1 ns

**Radio Frequency Quadrupole (RFQ)**

Quadrupole transport channel with longitudinal modulation to achieve accelerating field along the beam direction

- Injection energy: 12 keV/u
- Extraction energy: 600 keV/u
- Operating frequency: 80.5 MHz
- Power (CW): ~120 kW
ReA3 Cryomodules

Beta=0.085 cryomodule (2014)

Beta=0.041 cryomodules

Superconducting Quarter Wave Resonators
Operating frequency: 80.5 MHz

First cryomodule: 2 solenoid, 1 cavity
used for beam matching from RFQ

Second cryomodule: 6 accelerating cavities
acceleration up to 1.5 MeV/u (Q/A=0.25)
3 MeV/u (Q/A=0.5)
deceleration down to 300 keV/u

Commissioned acceleration voltage: 0.8 MV/cavity
(ReA specification value: 0.45 MV/cavity)
Reacceleration of charge-bred $^{39}$K ions

Energy spectrum measured by scattering from a foil into a silicon detector.

Reacceleration of charge-bred $^{87}$Rb ions from an offline source in the gas stopping area.

Residual gas ions (O, Ar) from EBIT with similar A/Q ratio can be used as pilot beams for tuning of the linac and the transport beam lines.

First two cryomodules (beta=0.041) are fully commissioned. Third cryomodule (beta=0.085) will be installed in 2014.
Achromatic beam transport and distribution line from ReA3 platform to multiple experimental end stations on ReA3 low energy experimental hall.

**Status:**

General purpose beam line is fully commissioned.

AT-TPC and south beam line will be finished this fall.

Flexible beam optics allows various experimental setups.
ReA3 Experimental Hall - Equipment

New hall accommodates existing equipment: LENDA, SeGA, GRETINA and smaller user provided setups.
First Experiment with Reaccelerated Rare Isotope Beam

NSCL experiment 13507 - August 2013

Excitation function of the $^{37}$K(p,p) reaction, measured with the ANASEN detector

$^{37}$K (76.7 MeV/u) rare isotope beam, produced by fragmentation of stable $^{40}$Ca (140 MeV/u) in A1900 fragment separator (focal plane rate: \( \sim 9 \times 10^6 \) pps)

$^{37}$K transported to gas stopping area, thermalized in ANL gas catcher, charge bred to $^{37}$K$^{16+}$ in EBIT charge breeder, reaccelerated with ReA3, and delivered to ANASEN (rate >500 pps)

Particle ID at experiment location
Conclusion

Reaccelerator facility at NSCL
Substantial progress with commissioning of gas stopping area, EBIT charge breeder, and the ReA3 reaccelerator allow experiments with reaccelerated rare isotope beams.

First user experiment with reaccelerated beam
Important milestone reached with delivery of a thermalized and subsequently reaccelerated rare isotope beam to an user experiment.

Future commissioning
Commissioning will continue with emphasis on reaching higher gas cell extraction and charge breeding efficiencies. Installation of third cryomodule in 2014 will allow achieving full energy of the ReA3 reaccelerator.
Outlook into the Future

The newly commissioned areas will become part of FRIB at Michigan State University:
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